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E-Vision decision support system implementation to match donors and recipients based on Gale-Shapely algorithm for Cornea transplantation surgery

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Abstract

In this paper, we propose to transform the traditional cornea transplantation methods into an electronic exchange between the cornea donors and recipients in the cornea transplantation elective surgery. Preferential evaluations of recipient and donors (individuals / eye-bank) satisfactions are mathematically modeled, then the preference matrix is used as input for Gale Shapely matching algorithm. The results of m*n match happens to be a very transparent approach in a bilateral e-cornea transplantation environment. These matched results are compared with the results obtained using Generalized Assignment problem which produces NP-hard approximated matches. It is found that the proposed method produces stable matching, which is preference based and strategy proof and it also reduces the need for number of iterations for matching.

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Keywords: DSS; Cornea; Transplantation; Donor, Recipient; Matching; Gale-Shapely;

1. Introduction

The Indian government and private organizations had established a large number of eye-banks for cornea transplantation surgery. It is estimated that there are around 160 such registered eye-banks [1] in India. Managing availability of all corneas that are eligible for cornea transplantation donated in the regulated areas has to happen under the proposed matching framework. Donating/receiving outside is not permitted. Under this system, the cornea donors or eye-bank can place the availability of the medically examined corneas for transplantation with the details such as location, lead-time, age, units and type of cornea transplantation and they are matched to recipients in need, who are registered with this matching system.

Matching DSS is created with the intention of providing cornea donors and recipients a centralized hub to donate the cornea of theirs' or their deceased relatives, and to ensure that after medical examination, they will be allotted to recipients who are in need. But over the years, this system has been monopolized by eye-bank who offers the organ or they will call for donors. Moreover, the medical examination should be performed over the cornea donated by cornea donors to validate whether the organ is eligible for the match and the cornea recipients have to wait for their turn of the allocation process (for several days / hours during the emergency / elective surgery). Burt [2] coined the term 'structural hole' to denote the separation and discrepancy that exists when two groups of people have no direct contact with each other. In this match network, on one side there is a group of cornea donors and on the other side, there are recipients who are in need. These two groups are not allowed to offer/receive directly with each other and are forced to transact via the matching network. Therefore there is a structural hole in the network.

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Table 1 given in Appendix illustrates the survey of Indian eye-bank for facilitating e-cornea transplantation elective surgery as listed below. There are no automatic mechanisms being implemented so far as proposed in this paper to match recipient and individuals / eye-bank (donor) with recipient fair play. A match-making web based system has been developed to match multiple cornea donors and multiple recipients in a typical cornea transplantation scenario. A MILP model has been created to match cornea donors and recipients in a match framework in [2], but, it is a typical implementation of generalized assignment, where allocation takes place in multiple rounds. It is solely based on availability. It is taken into account, the typical satisfaction (in terms of Donor age, lead-time, location etc.) of recipient/individuals / eye-bank (donor) into account while cornea transplantation in an M*N match-making environment, which is considered in our work. A mathematical model has been developed to assess preferential scores of two distinct players, which is given as input to the Gale Shapely match algorithm in Section 2. The results are discussed in Section 6. Finally, the conclusion is presented in Section 7.

2. Mechanism design for matching

We assume a set of recipients i = {1,2…,m} and set of cornea donors j = {1,2,…n}. Both cornea transplantation partners submit the attributes for their product to our web based decision support system (e-DSS) to find an optimal match. For a given organ of given quality level (based on age and result of medical examination) and promised lead time, the individuals / eye-bank (donor) must submit his true availability to the e-DSS as a private information, along with the parameters such as age, medical history, location and lead time. The recipients will not know the valuation of contending donors. Similarly, the hospital staff on behalf of cornea recipients will submit the requirement for their organ transplantation surgery of a quality grade (based on age) in a closed form, along with their promised lead time of acceptance. The satisfaction level of recipient and individuals / eye-bank (donor) is determined as follows:

2.1. Predicting quality of donor and recipient risk factors

Most cornea transplant surgeries are successful. But cornea transplant surgeries always have a small risk of complications, such as rejection of the donor cornea. [5] Based on several studies graft failure in earlier stages was the most significant risk factor that lead to secondary failure (P = .0013). The risk of failure was significantly decreased with increase in postoperative time. Patient risk factors for secondary failures in earlier grafts probabilities were significantly in the form of;

- race (P = .01),
- age (P = .004),
- iris color (P = .02),
- preoperative glaucoma medications usage (P = .0008),
- deep stromal vascularization (P = .002), and
- host horizontal diameter (P = 0.007).

Significant risk factors for failures that are associated with immunologic allograft reactions in initial grafts included factors such as donor size (P = .05), horizontal corneal diameter (P = .002), as the differences between horizontal corneal diameter, and both donor size (P = .02) and recipient trephination size (P = .01). However, deep stromal vascularization was only marginally significant (P = .09). Preoperative glaucoma medication usage in patient's history was not a significant risk factor. The relationship of the recipient's horizontal corneal diameter to immunologic graft rejection is a new risk factor that surgeons can directly control and thereby help avoid graft failure. To achieve this, the quality parameter for donor is computed using the parameters mentioned above in the scale of 1 to 5.

2.2. Evaluation of Recipient Satisfaction B_{ij}

$$r_{ij}=\{\sum_{a=1}^{k} w_i a * r_{ij} a\ ,\ 0\},\ r_{ij}a € (0,1); \quad (1)$$

where $r_{ij}a$ is fitness function for recipient "i" over donor j for attribute a. $w_i a$ is weight given by recipient "i" for attribute "a". The attributes considered by the recipient are age, location, quality value based on medical examination and lead time to offer. This demands true valuation of a product in terms of quality, lead time from the recipient and individuals / eye-bank (donor) respectively. This is modeled as follows:

More is better: (quality)

$$r_{ij}a = \begin{cases} 1,\ a_{ja} \geq ev_{ia} \\ \frac{a_{ja}-ev_{iamin}}{e_{ia}-ev_{iamin}},\ ev_{iamin} \leq a_{ja} < ev_{ia} \\ 0,\ e_{ia} < ev_{iamin} \end{cases} \quad (2)$$

Less is better:(lead-time)

$$b_{ij}a = \begin{cases} 1,\ a_{ja} \leq e_{ia} \\ \frac{ev_{iamax}-a_{ja}}{ev_{iamax}-e_{ia}}\ e_{ia} < a_{ja} \leq ev_{iamax} \\ 0,\ a_{ja} > ev_{iamax} \end{cases} \quad (3)$$

Where a_{ja}= actual value of attribute "a" given by individuals / eye-bank (donor) "j", e_{ia}= expected value of recipient "i" for attribute "a", ev_{iamin}= Min expected value of recipient "i" for attribute "a", ev_{iamax}= Max expected value of recipient "i" for attribute "a".

2.3. Evaluation of Donor Satisfaction Sji

Donor satisfies only on the allotment of recipient.

$$D_{ji} = \begin{cases} 1,\ L_{bi} > L_{sj} \\ \frac{L_{Di}-L_{Dj}}{L_{Dj}-L_{Djmin}}\quad ,\ L_{Djmin} \leq L_{Di} < L_{Dj} \\ 0,\ L_{Ri} < L_{Djmin} \end{cases} \quad (4)$$

Where L_{Ri} = actual match of recipient "i", L_{Dj} = expected match of individuals / eye-bank (donor) "j", L_{Djmin} = Min expected match of individuals / eye-bank (donor) "j". The calculated preferences R_{ij} and D_{ji} are used for preferential match using Gale Shapely algorithm. The GS algorithm calculates the number of matches over the registered donors and recipients using equation (5).

$$\text{No. of matches} = \sum_{i,j}^{m,n} m_{ij} \quad (5)$$

Where, m_{ij} = number of corneas for transplantation between matched individuals / eye-bank (donor) i and recipients j.

The following constraints are used in the mechanism design.

$$\sum_{i}^{m} m_i \leq q_i \quad (6)$$

The total number of units fetched from an individual / eye-bank (donor) is less than or equal to its demand.

$$\sum_{i}^{n} m_j \leq q_j \quad (7)$$

The total number of units allocated to recipients is less than or equal to its available units.

$$\sum_{i}^{m} m_i \leq \sum_{j}^{n} m_j \quad (8)$$

The number of units allocated does not exceed the number of units available.

When a recipient is interested in a quality k_i, it is okay if he is allocated a quality better than k_i. However quality k_i is determined using age, result of medical examination. When a donor has an organ of quality k_j, it is okay if his allocation is for a quality lower than k_j if he is getting the match at nearby location or lesser lead-time. (9)

When a recipient intends to receive organ in a lead time of l_i, it is okay if he receives it in a lead time lower than l_i. (10)

3. Match using Gale Shapely algorithm

Shapley's theory is based on marriage matching problem. In 1962 paper, Gale and Shapley explained this idea using the stable marriage problem [3]. In SMP it is asked how a number of women could be matched to a number of men, considering their respective preference value for each member of the opposite gender. They showed that regardless of the preferences, there would always exist a stable allocation. A stable allocation is one whereby no members can be better off by further exchange. Stability is property as it is viewed as an indication for efficiency because further improvement of satisfaction from exchange is not possible. In our application of match cornea donors and recipients, the recipients were chosen as the proposing member.

In this paper, we assume that cornea donors and hospital staff who puts requirements for recipients are rational individuals who participate to cooperatively choose an allocation. Under our customized GS algorithm, upon registration by recipient/individuals (donor) / eye-bank (donor), they receive the best possible organ that is available for allotment respectively based on their reported preference order. Hereafter, recipient/individuals (donor) / eye-bank (donor) allocation can never deteriorate. Furthermore, if in the future the allocation can be improved due to either party's cancellation. It follows that for every donor and recipient truthfully reporting its preference order is a dominant strategy. Hence, our customized GS algorithm is preference strategy-proof.

4. Matching constraints

i. Each recipient/donor must register their organ. Else they cannot post a match.
ii. A recipient/donor cannot offer/demand organ other than their registered organ. If a recipient/donor is registered in "Recipient-Donor" mode, then he can offer or receive organs as well.
iii. A normal recipient can submit requirement to get any of the available organ.
iv. If quantity exceeds threshold units of demand/supply (Threshold unit can be fixed by government personnel for normal organ exchange between recipient and donors in admin login console form) Eg: if it is 250 units per day, if recipient demands for 500 units he should give explanation before submitting a match.
v. Options are provided to source from multiple donors.

5. Delivery/Acceptance acknowledgement

Once organs are offered by individuals / eye-bank (donor), donors must acknowledge for their offerings. Similarly, once delivered organs are received by recipient, they must acknowledge for receiving the organs and should submit feedback forms which have fields to tell about donor, about late shipments, deteriorated quality of promised entities, report of wrong quantity and for loss incidents. Based on the feedback we will rate both the recipient as well as donors.

5.1. Additional Measures

We routinely audit our signups using programmed internal mechanisms, matching rosters for strings of email addresses that come from the same private domain. We also look for similar names, usernames, and "local-parts" of email addresses across domains using internal mechanism. We also show matching result updates instantly, we collect loyalty feedback from both sides. That way, if someone is trying to cheat, based on feedback questionnaire we evaluate the users, and unless they went big, they won't know for sure if their method was successful. We try to be as much of a "black box" as possible since match works internally.

6. Experimental results

Assume a sample input as given in Table 2. There are 5 Recipients and 7 Donors. Assume for all above records the organ type as “EYE”, organ name as “Cornea” and city as “CHENNAI”. Take a count of distinct CITY based on organ name. For above inputs the count will be 1 since all are of same type.

Table 2: Input table

USR_ID	NO. OF EYES	MIN_LEAD_TIME (Mins)	MAX_LEAD_TIME (Mins)	QUALITY	MATCH_TYPE	MATCH PRIORITY
BS31	1	50	75	3	RECIPIENT	200
BS32	2	65	75	1	RECIPIENT	350
BS33	1	60	80	1	RECIPIENT	235
BS34	1	55	65	1	RECIPIENT	340
BS35	1	60	80	1	RECIPIENT	100
BS36	1	60	80	1	DONOR	150
BS37	2	50	80	2	DONOR	200
BS38	1	65	90	2	DONOR	150
BS39	1	55	80	1	DONOR	300
BS40	1	65	90	2	DONOR	200
BS41	1	62	78	1	DONOR	100
BS42	1	61	82	1	DONOR	120

The numbers of allocations are calculated iteratively over several rounds until there are either no recipients / donors for cornea transplantation.

6.1. Comparison with Generalized assignment problem

The proposed algorithm was compared with the mathematical formulation given by [2] for an Generalized assignment mechanism for implementing recipient/donor match in an e-match implementation. Constraints (6) to (10) presented in section 2 are checked for validity. Table 2 is given as input and the results are given in Tables 3 through 7 for various rounds of implementation. After completion of a round, donors and recipients who have been allocated the items are removed from the system. For the next round, the donors are given an opportunity to change their offering based on the demand observed in the first round. Similarly, the recipients are given an opportunity to increase their requirement, and the next round proceeds. This process continues as long as recipients are present in the system or until all requirements are matched. Total number of donors stagnated at the end of round 5 is 4.

Comparison		General assignment model	Proposed GS Model
No of rounds of allocation		5	2
Net allocation (Avg)		300	312
Performance Metrics	Time Averaged for allocation	60ms	71ms
	Recipient/Donor stagnation	3 D 3 R	4 D 0 R

Table 2: Fnal Allocation results

The comparison results of the proposed modified GS algorithm with preferential inputs were compared with classical Generalized-assignment model proposed by [2] and tabulated in Table 2. It is thus inferred that the proposed model is better in terms of reducing the number of rounds of allocation at the end of all rounds and minimizing the stagnation of donors /recipients at the end of allocation. The results produced by generalized assignment are always approximated to NP-hard and hence the allocation seems to be higher side, but it is a variable and depends on the random match variation by the donors. Whereas, the minimum guaranteed profit can be arrived in the proposed model. Also, the performance metric is chosen as “Time averaged allocation (TAA)”. With the assumption that every round of allocation (R) is done at the end of every time period ‘t’, TAP = Net allocation/R. When large number of multiple users updates matches in every round of allocation, system will face insert, update anomalies, whereas our proposed system will don’t have any such issues.

7. Conclusion

When there is no match exists (D, R) it is said to be a stable match by which both D and R are individually better than they would be with the element to which pairs are matched at present. This is achieved in this bilateral cornea transplantation scenario of matching recipients and donors with individual preferences. If the participating agents, recipients / sellers are rational and submit their true valuation of a multi-unit, single indivisible product to the decision support system (DSS), it is more likely that they get stable matches of allocation. The proposed method allows these registered persons to submit their availability/requirements in the form of [units, location, lead time] instead of the traditional Generalized assignment model of submitting matches in the form of [fixed individuals / eye-bank (donor)] in first round, which is then varied every round by the user to find an optimal match. Since, the offers/requirements are submitted as a private information to the DSS, it is more likely to make the allocation cheat-proof and produces matches in less number of rounds. Finding the best match solely depends on the true valuation of organs by the user. Also, the customized Gale Shapely algorithm has been applied to produce optimal matches in a bilateral cornea transplantation scenario, which is first of its kind application in an e-cornea transplantation environment. Compared to many e-elective surgery portals, the proposed model seems to be more realistic and transparent to the users in match donors and recipients. This DSS is first of its kind implementation for the e-cornea transplantation elective surgery.

We further would like to make our e-portal to take the complete governance responsibility and act as the key interface in selecting partners, setup and evaluate performance metrics of the players, maintain accountability of material and services, provide feedback on operational status for the prospective development of its players.

In this work, we have taken only the boundary values of the submitted offers/requirements to finalize the match. In our future work, we aim to build in Genetic algorithm to vary the offers/requirements from the submitted parameter ranges of the donor/recipient respectively to maximize the allocation.

Appendix

Website	Drawbacks
http://ebai.org/	Only users can register. No matching mechanisms are available
eyebank.lvpei.org	No matching mechanisms for donor and recipient are available.
http://donateeyes.org/	Only donors can register themselves. There is no background mechanism for cornea allocation.

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